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RECORDING USING HOLOGRAM ARRAYS:
a general survey

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RECORDING USING HOLOGRAM ARRAYS: A GENERAL SURVEY

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Summary

The theoretical and practical aspects of using holographic techniques in both analogue and digital recording systems are examined, and comparisons are made between holographic and other present-day or proposed methods of recording.

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RECORDING USING HOLOGRAM ARRAYS: A GENERAL SURVEY

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1. Introduction

Holographic techniques have been described in detail elsewhere.[1,2,3,4] Briefly, a hologram consists of a recording, on photographic film or other suitable* light-sensitive material, of part of the interference pattern formed in the common volume occupied by two distinct components of coherent radiation, initially derived from the same source (usually a laser[5,6]). This recording can either be two-dimensional (i.e. a cross-section of the interference pattern, giving rise to a 'surface' hologram) or three-dimensional, in which the thickness of the recording medium is large relative to the 'scale' (or average distance between corresponding features) of the interference pattern and from which a 'volume' hologram is formed. The distinction between the two components of radiation contributing to the interference pattern lies in the paths traversed in each case. The path of one component includes reflection from (or transmission through) the object whose image is to be stored holographically. The other component (the 'reference beam') has a well-defined path whose geometry can be readily duplicated. When the hologram is illuminated by a 'reconstruction beam' of radiation having the same wavelength and geometry as that of the original reference beam, diffraction occurs from the grating-like structure formed by the recording of the interference pattern, and this diffracted component gives rise to an image of the original object. This image occupies the same position in space, relative to the hologram, as did the original object. Differences between reconstruction- and reference-beam parameters may give rise to distortions in image scale and geometry, and in the case of volume holograms such differences (particularly between the angles of incidence of the two beams) may suppress image reconstruction completely. Other images of the object (often distorted) may also be formed.

If the object in a holographic system has diffuse reflecting or transmitting properties, radiation from each point of the object will arrive at every point of the light-sensitive recording material. Information about each object point is therefore 'spread' over the whole hologram** giving considerable immunity to the presence of blemishes, dust particles, etc. on the hologram. To illustrate this point, consider the case of the holographic reproduction of a two-dimensional object situated in a plane parallel to, but separated from, that of the recording medium itself. The reconstructed image (I in Fig. 1) will occupy a position relative to the hologram (H) identical to that of the object

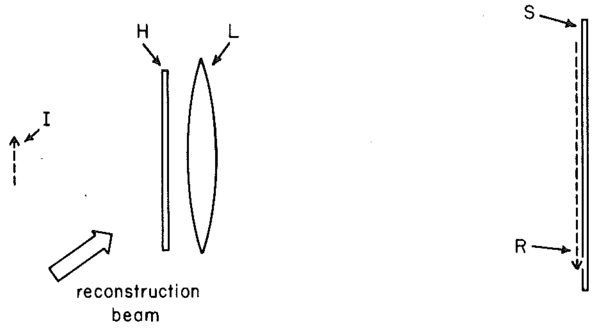

Fig. 1 - Re-imaging of holographic image
I – *Reconstructed image*
H –*Hologram*
L – *Lens*
R – *Final real image*
S – *Screen*

If a lens (L) is placed close to the hologram, a final real image (R) of the reconstructed image may be formed on a screen (S), while the hologram itself will (if the lens is of sufficiently wide aperture) be well out of focus. Blemishes, etc. on the hologram will therefore not appear on the screen, and the image R will be free of defects from this cause. Such blemishes will, however, contribute to the overall flare or 'veiling glare' of the lens system. Furthermore, if only part of the hologram is illuminated by the reconstruction beam, the whole image will nevertheless be reproduced: the resolution of image detail will, however, be reduced since the effective area of the hologram will have been reduced to that of the illuminated portion.

When discussing recording systems, two classes of recording technique may be distinguished:

(a) Analogue recording, in which the recorded information is related to the original information* by a continuous mathematical function.

(b) Digital[7a] recording, in which the original information is sampled at suitable time intervals and the magnitude of each sample is recorded in numerical form.

In the analogue recording of television signals, a further distinction may be made between 'picture' recording, in which the recorded information takes the form of recognizable images of the displayed picture[8], and 'waveform' recording in which the recorded information is an analogue of the electrical video signal.[9,10] Sound analogue recording, whether electromechanical (disc), electro-magnetic (tape) or electro-optic (film)[11,12,13] is always a 'waveform' process. Since analogue recording techniques are very well established, a new system making use of holographic techniques must show a worthwhile advantage over the more conventional methods in order to gain acceptance.

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*The recording may take the form of variations of optical transmission of the processed recording medium (an 'amplitude' hologram), or alternatively may consist of variations in the thickness of refractive index of the recording medium, giving rise to corresponding phase variations in the transmitted radiation (a 'phase' hologram). Opaque materials may also be used, the recording being in the form of an embossed pattern.

**Use of this technique gives rise to a 'diffuse' hologram

*e.g. sound pressure level in sound recording or light flux in television recording.

In the more recent field of digital recording, a review of techniques for recording digital television signals has been made by Lunn and Moffatt[14], and a prototype digital sound recorder has been described by Bellis and Jones[15]. Digital recording is essentially a 'waveform' process, although in a system proposed by Hacking[16] for recording digital television signals, analogue information could in principle be re-introduced to facilitate the editing of recordings, given a photographic film stock with suitable charateristics.

2. Analgoue recording

The reconstructed holographic image may be used as a basis for a system of 'picture' recording of television signals. Each television picture has first to be recorded on conventional motion-picture film and a hologram is then prepared from each film frame. Although at first sight appearing unduly cumbersome, this process in fact involves no more stages than is required when an optical telerecording is made using a 'negative-positive' film process. Its principal advantage is that non-photographic materials may be used as the recording medium, and advantage may be taken of the greater durability of these materials when making recordings for archival purposes: holograms could, for example, be prepared on metal surfaces. Assuming that a phase hologram is prepared (see footnote on p.1), it can be shown[3a,17] that if the hologram causes relatively small phase changes of the reconstructing-beam light, and if these phase changes are proportional to the holographic interference-pattern intensity during the preparation of the hologram, then a distortion-free* holographic image will be produced. The first of these conditions can be achieved by suitable choice of exposure of the recording medium, while the second conditions is ensured by utilizing only a small part of the overall transfer characteristic (the relation between exposure and the resulting phase change of the reconstructing illumination) by arranging that the reference beam is of much greater intensity than the light from the object. Under these conditions the holographic image will remain distortion-free even if long-term changes take place in the transfer characteristic of the material. As the object (film frame) is transparent, non-diffuse object illumination may be used and the speckle-pattern** effects associated with the scatter of coherent light from diffuse objects will be absent. The advantages of the use of diffuse object illumination (see Section 1) may be largely retained by illuminating the transparent object with a number of non-diffuse beams of light, mutually inclined to each other at relatively small angles. Each of these beams gives rise to a separate hologram on the recording medium[17,18] and the geometry of the system is arranged so that these 'sub-holograms' do not overlap. The reconstructed images from each sub-hologram coincide to form the final reconstructed image, while the redundancy of information provided by the use of a number of sub-holograms gives protection against the appearance in the image of effects due to blemishes in the optical system or on the hologram itself. The required multiple-beam illumination may be obtained by the use of a mirror system, or alternatively by the use of a one- or two-dimensional phase grating placed behind the object[17,19]. Colour information may be carried by illuminating the object and the recorded hologram with coherent light of each primary colour and arranging (by using colour selective filters as in Collier and Pennington's method[20]) that any one sub-hologram is formed by light of only one primary colour and is illuminated with light of the same colour during image reconstruction.

Apart from the advantage of extreme durability, which may, as discussed above, find an application in the preservation of pictorial information for archival purposes, the use of holographic techniques does not seem to offer any advantages over other well-established methods of analogue television recording. Because holography is essentially 'pictorial' in character, in that a physical object and an image of that object are involved, it is not suitable for directly recording analogue information in 'real time' (i.e. at the same rate as the information is made available). It is therefore not applicable to analogue sound recording, which is always a 'waveform' process, or to 'waveform' television recording.

3. Digital recording

3.1 Summary of principles of digital transmission

In the process of 'analogue-to-digital conversion', the original signal must be sampled at least twice in the period of time occupied by one cycle of its highest permitted frequency.[7b] A group of pulses must then be used to describe the magnitude of each such sample, usually in binary digital form. The accuracy with which this sample magnitude is so described is determined by the number of binary digits in the group. If these pulses are transmitted in serial form (i.e. in succession through a single transmission path) the bandwidth of the resulting 'digital signal' will be greater than that of the original analogue signal.* It is convenient to define the required bandwidth in terms of the information flow, measured in terms of the rate of flow of binary digits or 'bits' through the transmission path. In the case of digital television signals,[14,21] for example, the information flow is about 10^8 bits per second, while for a stereo sound signal[22] the flow is about 10^6 bits per second.

At the receiving terminal of a digital transmission system, each group of incoming binary digit pulses is used to generate a pulse of magnitude equal to the corresponding sample of the original analogue signal, within the limits of accuracy imposed by the number of pulses in the group. The analogue output signal is obtained by low-pass filtering the resulting train of regenerated variable-amplitude pulses. The inaccuracies in regenerating the original sample magnitudes give rise to a noise-like component[7c] added to the regenerated analogue signal (the so-called 'quantising noise')' Provided that the signal-to-noise ratio of the digital signal at the input to the receiving terminal is sufficiently high to enable the presence or absence of each pulse to be recognised unambiguously, the quantising noise constitutes the only noise component of the regenerated signal. The effect of noise in the transmission channel is to cause errors in the recognition of incoming digital information. It has been found that, using appropriate error-concealment techniques, an error rate* of 10^{-4} can be tolerated in a digital television system[39] and an error rate of 10^{-5} in a sound system,[40] corresponding to ratios of peak signal to r.m.s. white noise in the transmission channel of about 18 dB and 19 dB respectively[7d]. These values may be compared with the signal-to-noise ratios of the regenerated analogue signals of 55 dB for television[41] and 81 dB for sound.[40]

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*i.e. correct reproduction of the relative intensities of light from different parts of the holographic image.

**A random granular pattern produced by mutual interference between components of reflected light emanating from different elementary portions of the surface. This pattern is recorded on the hologram along with the wanted interference pattern.

* The bandwidth is the product of the sampling frequency and the number of digits (including parity digits[42]) used to describe the sample magnitude.

From the foregoing description it can be seen that a digital transmission channel requires a considerably wider bandwidth than the corresponding analogue channel, but can have a very much lower signal-to-noise ratio. Furthermore, the digital system lends itself to the transmission of signals over long distances, since a set of repeaters placed at intermediate points on the route can regenerate the digital information and in each case entirely eliminate the noise component of its incoming signal.[7e] Distortion- and noise-free transmission (within the limits imposed by quantising noise) can therefore be obtained over such transmission paths.

3.2 General comments on digital recording

The facility, mentioned above, of digit-signal regeneration has led to interest in digital recording systems. By proper choice of the regeneration process, the reproduced signal can in principle be made free of all defects normally associated with analogue recording systems.[15] Unfortunately, recording systems are, by their nature, devices of limited bandwidth. The incoming information (whether analogue or digital) is retained in the recording medium as spatial variations of some property of the medium, and in all cases an upper limit is placed on the spatial frequency which can be retained by the medium. This limit may be intrinsic to the medium itself, or may be due to limitations in the methods used to write the information onto the material or read it off again; in practice all such limitations are usually effective. In discussing digital recording techniques it is convenient to describe this limitation of the recording process in terms of the 'packing density' of the information on the recording medium, or in other words, the number of binary digits that can be recorded on (and recovered from) unit area of the recording medium. An estimate of the packing density that could in principle be achieved using a holographic digital recording system is made in Section 3.4.

Digital recording systems may be used for both sound and television applications. Although the discussion which follows in Sections 3.3–3.6 is directed towards the more difficult problem (in terms of rate of information flow) of recording digital television signals, digital techniques could also be of use for recording sound signals. In both cases, for example, copies of a digital recording held for archive purposes could be made at intervals, so as to offset the effects of long-term deterioration of the recording medium. This process is analogous to the insertion of repeaters in a long-distance transmission system (see Section 3.1), and would enable the recording to be preserved without loss of quality.

3.3 Principles of digital holographic recording

In the basic digital holographic recording system a number of 'digit beams' of coherent light (B_1, B_2 . . . in Figure 2) are incident at different angles onto the recording medium[23,36]. Each beam is associated with the digit having a particular degree of significance in a digit 'word': thus the beam B_1 may correspond with the least significant digit in the word, the beam B_2 with the next degree of significance, and so on. A reference beam (B_{ref}) is also incident onto the recording medium. All the beams are derived from the same coherent source by suitable light-splitting arrangements. Interference takes place between the reference beam and each of the digit beams. Each digit beam can be either transmitted or obstructed by a light valve (V_1,V_2. . .) controlled by the appropriate digit signal. The resulting hologram will consist of a number of superimposed fringe patterns, each pattern corresponding to one of the digit beams reaching the recording medium. For example, if each beam is accurately collimated, a set of grating-like patterns will be produced, each being distinguishable by its spatial frequency or orientation (or both such parameters). In Figure 2 the

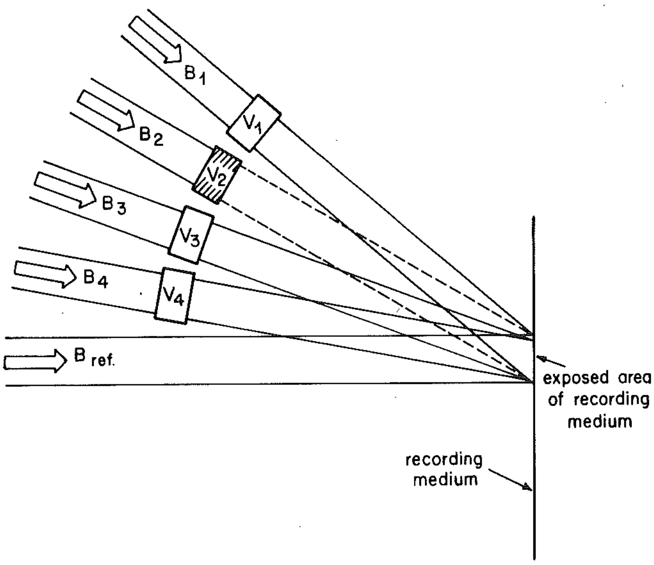

Fig. 2 - Making a digital holographic recording: basic principles

B_1,B_2, ... – *Digit beams*
B_{ref} – *Reference beam*
V_1, V_2 . . . . – *Light valves*

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*Expressed as the probability of erroneous recognition of any one digit pulse.

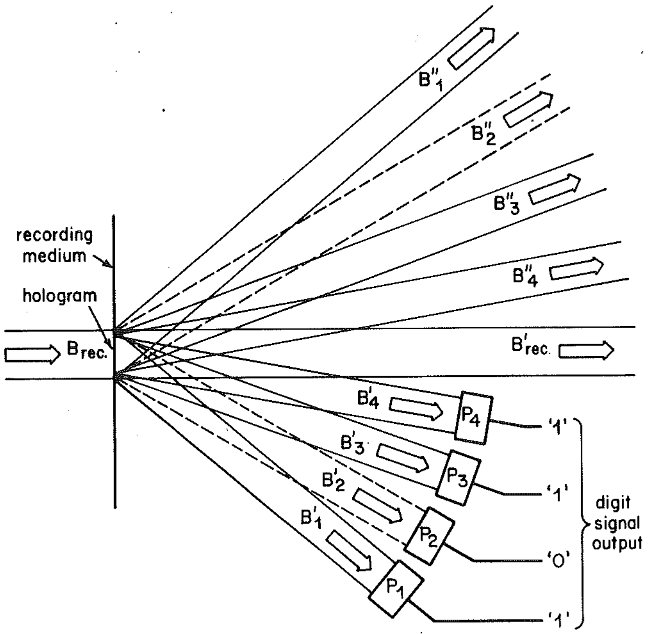

Fig. 3 - Replaying a digital holographic recording: basic principles

B_{rec} – *Reconstruction beam*

B_1', B_2', . . . – *Reconstructed digit beams*

B_1'', B_2'', . . . – *Reconstructed 'twin wave' beams*

P_1, P_2, . . . – *Photoelectric cells*

digit word 1101 is shown being recorded, beam B_2 being obstructed and the other beams transmitted by their respective light valves.

When the processed hologram is illuminated by a reconstruction beam (B_{rec} in Figure 3), diffraction occurs at each of the fringe patterns and the digit beam incident during the recording are reconstructed (B_1', B_2', . . .). The 'twin wave' beams B_1'', B_2'', . . . may also be reconstructed[1,3] and the residual reconstruction beam B'_{rec} will also be present. Photoelectric cells P_1, P_2, . . . detect the presence or absence of each reconstructed digit beam.

During the formation of the hologram interference will also take place between each pair of digit beams, and the patterns thus recorded on the hologram will give rise to spurious 'intermodulation' diffracted beams on reconstruction (not shown in Figrue 3). Their intensity may in some cases be enhanced by the geometrical symmetry of arrangement of the digit beams (for example, if the angles between adjacent digit beams are all equal, the intermodulation components due to interference between each pair of adjacent beams will all be superimposed to form one relatively intense spurious component). This effect may be reduced by arranging[24] that a random phase relationship exists between the various digit beams arriving at the recording medium, by appropriate adjustments of the optical path length. In any case, the geometry of the system must be arranged so that no spurious beam of significant intensity can fall onto a photoelectric cell.

Instead of using light valves to control the digit beams during the recording process, a 'fringe spoiling' technique may be used in which the position of the relevant interference fringes relative to the recording medium is changed during the exposure of the medium.[16,23] A blurred recording of the interference fringes is thus obtained resulting in a reduced modulation depth of the recorded pattern. The extent of this reduction depends on the amount and nature of the movement of the fringe pattern[3b] but can be arranged to eliminate the recording of the pattern completely. The corresponding reconstructed digit beam will therefore be absent. Another method of digit-beam control consists of arranging that the reference beam is plane polarised, and that the polarisation of each digit beam can be either parallel to that of the reference beam (in which case interference takes place between the two beams) or perpendicular to it, in which case no interference takes place. Both these methods of recording the digital information have the advantage that the mean exposure of the recording medium does not vary with the value of the recorded digital word: this is an advantage since work by Hacking has shown that only a rather restricted latitude of exposure of the medium (±½ stop) can be permitted for satisfactory recording of the interference fringes.

In practice the recording medium itself must move between successive exposures, and arrangements must be made to ensure that this movement does not significantly reduce the modulation depth of all the recorded interference patterns. One such arrangement is to use a very short exposure time (e.g. by using a Q-switched laser[6,25]); alternatively, the movement of the medium can be made to be parallel to the individual lines in the fringe patterns. The use of a very short exposure time would make the above-discussed fringe spoiling technique very difficult to implement.

3.4 The maximum packing density of a holographic recording system

In a holographic recording system, a succession of holograms will be recorded side-by-side on the recording medium. The calculation of the packing density of the recording system (see Section 3.2) therefore resolves into obtaining the product of the number of binary digits in each hologram and the number of holograms on unit area of the recording medium.

The information capacity of a single hologram clearly depends on the size of the hologram and the resolution of the recording material (i.e. the highest spatial frequency that the material can accommodate). A number of authors[3,26,27] have discussed this subject: the following treatment is based on the method used by Smith.[3c]

Consider a square, transparent surface hologram of side H, uniformly illuminated by a collimated reconstruction beam normal to the surface of the hologram. Let λ be the wavelength of the illuminating radiation. Assume that the recorded diffraction patterns consist of sets of parallel straight lines, so that the reconstructed beams would also be collimated if H was very large.

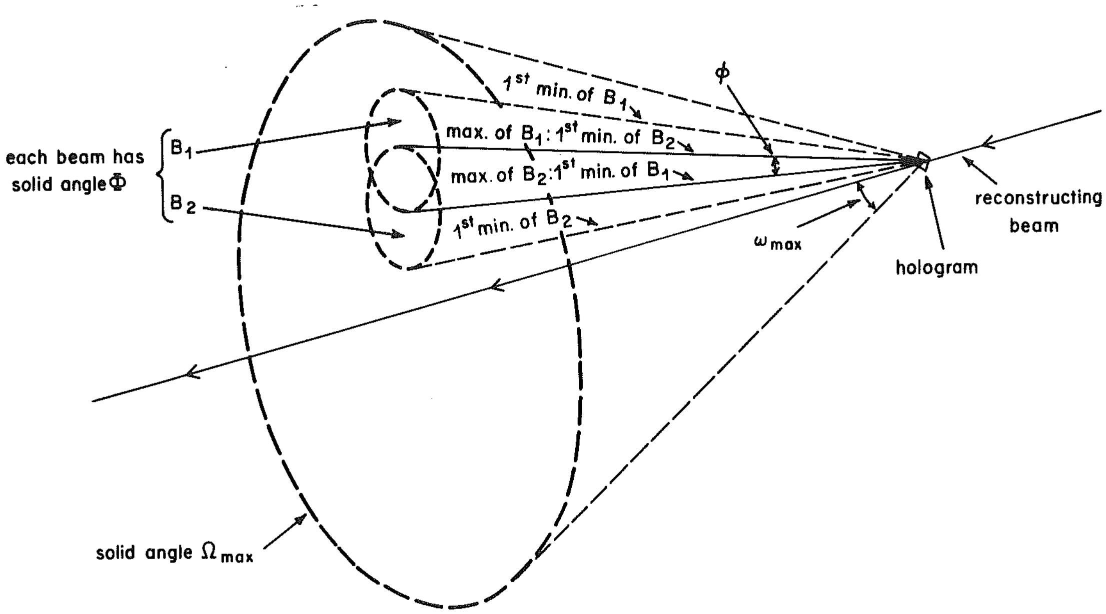

Fig. 4 - Cones of radiation from a small hologram with limited resolution

In practice H is not large, and diffraction occurs due to the hologram acting as a finite aperture. Each reconstructed beam will therefore diverge: at distances from the hologram large compared with H the intensity profile of each beam will contain maxima and minima. Using the Raleigh resolution criterion, two adjacent beams (B_1 and B_2 in Figure 4) are considered distinguishable from each other when the direction of maximum intensity in one beam coincides with the direction of the first minimum of intensity of the other beam. Under these conditions the angle ϕ between the beams is given[28,29] by

$$\sin\phi = \frac{\lambda}{H} \qquad (1)$$

(Strictly speaking this equation only applies to sets of beams in planes parallel to the hologram edges and in directions nearly normal to the hologram surface: however, for the present order-of-magnitude estimate it will be taken as applying to all beams emerging from the hologram). The solid angle Φ occupied by one beam is therefore given by

$$\Phi = 2\pi(1 - \cos\phi) \qquad (2)$$

If the resolution of the recording medium is restricted to a spatial frequency of n_{max}, it can be shown (Equation 2, Ref 1) that reconstructed beams cannot emerge from the hologram making an angle to the normal greater than ω_{max}, where

$$\sin\omega_{max} = \lambda n_{max} \qquad (3)$$

The solid angle Ω_{max} which may be occupied by reconstructed beam is therefore given by

$$\Omega_{max} = 2\pi(1 - \cos\omega_{max}) \qquad (4)$$

Thus the number of resolvable beams (N_{max}) that can occupy this space is given by

$$N_{max} = \frac{\Omega_{max}}{\Phi}$$

$$= \frac{1 - \cos\omega_{max}}{1 - \cos\phi} \qquad (5)$$

In practice, the hologram dimension H is likely to be much greater than the wavelength λ of the illuminating radiation; hence from Equation 1 $\sin\phi$ (and therefore ϕ) is very small, and this equation may be written

$$\sin\phi = \phi = \frac{\lambda}{H} \qquad (6)$$

furthermore, because ϕ is small,

$$1 - \cos\phi = \frac{\phi^2}{2} \qquad (7)$$

Hence Equation 5 becomes

$$N_{max} = \frac{2H^2(1 - \cos\omega_{max})}{\lambda^2}$$

Since a surface hologram is under consideration, each interference pattern recorded on it will give rise to two reconstructed beams, corresponding to the wanted and 'twin wave' holographic images[1,3]. Hence the number of different interference patterns that can be recognised (and therefore the number of binary digits (B_{max}) that can be recorded on the hologram) is given by

$$B_{max} = \frac{N_{max}}{2} = \frac{H^2(1 - \cos\omega_{max})}{\lambda^2} \qquad (9)$$

Since $\sin^2 x + \cos^2 x = 1$, Equation 3 may be written

$$\cos\omega_{max} = [1 - (\lambda n_{max})^2]^{½}$$

Hence Equation 9 becomes, in terms of the original maximum spatial frequency n_{max} that can be laid down on the recording medium

$$B_{max} = \frac{H^2}{\lambda^2}\left\{1 - [\,1 - (\lambda n_{max})^2]^{½}\right\} \qquad (10)$$

An interesting feature of Equation 10 is that it shows the number of binary digits that can be carried in one hologram to be dependent on H^2 or in other words on the area of the hologram. The theoretical packing density of the holographic recording system is thus independent of the size of the individual holograms, provided that no recording-medium surface is left unexposed between these holograms. For Helium-Neon radiation (λ = 632·8 nm) Equation 10 leads to the result that for a recording medium limited in resolution to a spatial frequency of 1000 cycles/mm the greatest possible packing density of the order of 5×10^7 bits/cm^2.

It is interesting at this stage to compare this theoretical result with the packing density actually achieved by Langdon[27], who found that 10^4 digit beams could be distinguished when reconstructed from a circular hologram 0·6 mm in diameter. Assuming these holograms to be arranged for best use of the surface area of the recording medium (i.e. with their centres at the vertices of equilateral triangles) this would give a packing density of 3.2×10^6 bits/cm^2, or about one-sixteenth of the theoretical value. There appear to be two reasons for this reduced value of packing density. In the first place, the area of hologram required to give adequate separation of the digit beams was found by Langdon to be four times the value predicted by use of the Raleigh criterion. In the second place, Langdon's method of generating the digit beams during recording and reading them during reconstruction (see Section 3.5.1) places a limit* on the value of ω_{max} (Equation 3) which is lower than the value obtained by assuming that the recording medium is limited in resolution to 1000 cycles/mm. As this second limitation is brought about by instrumental difficulties which could in principle be overcome (e.g. by using more than one lens system) it seems reasonable to assume that the practical upper limit on the packing density, for a recording medium with resolution limited to 1000 cycles/mm, would be of the order of 10^7 bits/cm^2.

The discussion so far has been concerned with surface holograms. If the recording medium is suitable for preparing volume holograms, Bragg-angle effects[1,3] can be used for two purposes. In the first place reconstruction of the unwanted 'twin wave' digit beams is suppressed, and the storage capacity of the hologram is therefore doubled. In addition, a number of holograms can be superimposed during recording, using differing reference-beam angles of incidence for each individual hologram: image reconstruction will only occur if the reconstruction- and reference-beam angles of incidence correspond. The necessary degree of such correspondence depends (among other factors) on the thickness of the recorded hologram. For a thickness of 100 wavelengths (e.g. 63 μm for Helium-Neon radiation) differences in reconstruction-beam angles of incidence of the order of [3d] four degrees will enable the individual holograms to be distinguished from each other. This suggests that the limit to the number of individual holograms that can be superimposed will be set by the transfer characteristic of the recording medium rather than by restrictions in the choice of reference-beam angle. If ten** individual holograms are recorded in this way[30], the theoretical packing density is increased by a factor of 20 and becomes 10^9 bits/cm^2, while the practical upper limit, as discussed above, similarly becomes 2×10^8 bits/cm^2.

The use of volume holograms becomes even more advantageous if very thick recording media are used. Van Heerden has estimated[31] that a total of 10^{13} bits/cm^3 may be stored in a suitable crystalling material. It does not appear that this degree of three-dimensional packing density has yet been achieved in practice, although a system[32] giving a potential storage capacity of 10^{12} bits/cm^3 has been announced.

3.5 Practical considerations

3.5.1 Optical arrangements

A number of arrangements may be used for generating the individual digit beams (see Figure 2). One method is to use a relatively coarse diffraction grating, giving a uniform distribution of energy through many orders of diffraction: an array of small parallel cylindrical lenses embossed on a transparent film has proved suitable[23] for this purpose. If the number of digits per hologram is very large, a more convenient arrangement[27] is to provide a 'digit plate' (P in Figure 5) consisting of an array of holes in an otherwise opaque medium. This plate is rear-illuminated with a beam of coherent light (B_{illum}) and is placed in the focal place of the object lens (L_o). Some method is provided for causing the light passing through each hole to diverge: for example, a diffuser may be placed behind the plate, or the plate may be illuminated with a number of non-diffuse beams inclined to each other as discussed in Section 2. Alternatively, enough divergence of the light may be obtained by diffraction at the digit-plate holes. Each hole in the digit plate acts as an individual source and gives rise to a 'quasi-collimated' beam* ($B_1, \dots\dots B_n$) after passing through the object lens, the angle made by the beam to the axis of the optical system being determined by the position of the hole in the digit plate. These beams converge at the focus (F_o) of the object lens, where the holographic recording medium (R) is placed. A reference beam (B_{ref}) of greater intensity than the digit beams also falls on the holographic recording medium at this point (although shown as emanating from a separate source in Figure 5, it could be generated from another hole in the digit place with suitable adjustment of relative intensities). A mask M restricts the size of the recorded hologram to the required value.

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*Because of practical limitations in the apertures of the lenses used in the optical arrangement.

**The superposition of up to seven analogue holograms is described in Reference 30: it seems reasonable to assume that at least ten digital holograms could be superimposed.

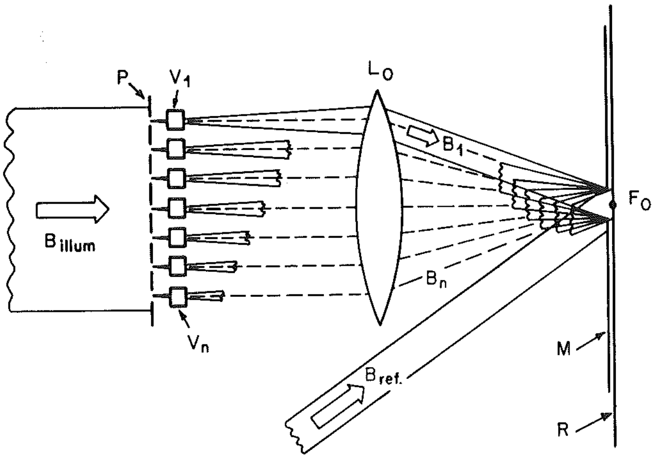

Fig. 5 - Making a digital holographic recording with a large number of digit beams

B_{illum} – Illuminating beam
*$B_1 \dots B_n$ – Digit beams***
B_{ref} – Reference beam
$V_1 \dots V_n$ – Light Valves
L_o – Object lens
M – Mask
R – Recording medium
F_o – Focus of object lens

***For clarity only digit beam B_1 is shown in full*

The system described by Langdon[27] involved the simulation of a 'read-only' memory, the digit plate consisting of an array of transparent square areas on an opaque background, some of the transparent areas being 'blacked out' to simulate logical 'noughts'. In a fully-developed read-only memory a number of digit plates would be used (one per recorded hologram), each with the appropriate pattern of digital 'ones' and 'noughts' drawn on it. For a real-time recording system, all the holes in the digit plate would be present and an array of light valves ($V_1, \dots \dots V_n$) adjacent to the plate would control each digit beam.

The photoelectric cells ($P_1, \dots . P_n$ in Figure 6) used to recover the digital signals from the reconstructed digit beams ($B_1', \dots . B_n'$) during playback of the recording are most conveniently constructed in an integrated array if the number of digits per hologram is large. A lens system (L_I) is therefore required to image the reconstructed digit beams onto this array. With a small number of digit beams it would be feasible to use separate photocells placed directly in the paths of the reconstructed digit beams. The reconstruction beam (B_{rec}) is incident onto the holographic recording medium (R) at the same angle as the reference beam used in the recording process. In fact, the same equipment could be used for both recording and playback: during playback the beam B_{illum} (Figure 5) would be absent, while during recording the photocells ($P_1 \dots P_n$ in Figure 6) would provide a monitoring facility if the recording medium was partially transparent.

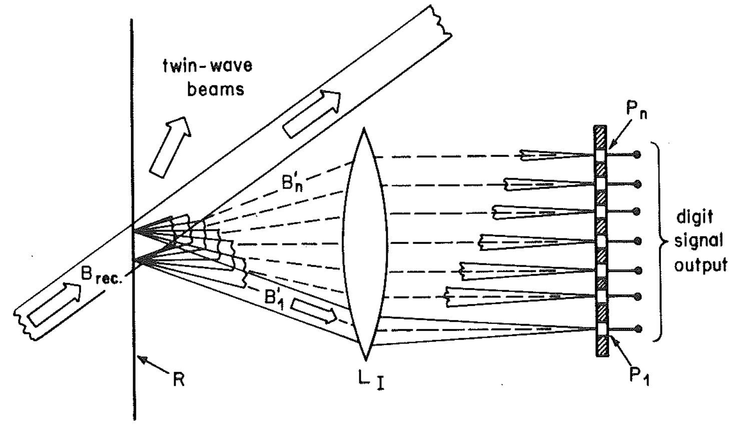

Fig. 6 - Replaying a digital holographic recording using a large number of digit beams

B_{rec} – Reconstruction beam
*$B_1' \dots B_n'$ – Reconstructed digit beams**
R – Recording medium
L_I – Imaging lens
$P_1 \dots P_n$ – Photo-electric cells

**For clarity only the reconstructed digit beam B_1' is shown in full and the twin-wave beams (cf. Fig. 3) are not shown in detail.*

The apertures of the lens system used during recording and playback impose restrictions on the greatest angle of incidence of the digit beam which can be used during recording and the greatest angle of emergence of the reconstructed digit beam which can be accepted during playback. It may be necessary to use a number of suitably disposed optical systems, with the axis of each system inclined to the axis of the complete equipment (i.e. the normal through the surface of the recording medium), in order to make full use of the resolution capabilities of the recording medium.

3.5.2. The sequential recording and playback of individual holograms

For the purposes of obtaining an order-of-magnitude estimate of the writing and reading velocities,** assume that Langdon's result[27] of holding 10^4 binary digits in a hologram 0·6 mm in diameter can be achieved. As the information flow of a digital television signal is 10^8 bits/second, 10^4 holograms per second will be required and the writing velocity will therefore be 6 m/sec (240 in/sec).

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*Strictly speaking the beam is collimated only when the digit-plate hole is very small, and acts as a point source.

**The relative velocity between the recording medium and the writing or reading optical systems. For real-time recording and playback these velocities are the same.

Considered as the velocity of the recording medium itself in the form of tape, this value is excessive: in addition, the tape width (say 1mm or 1/25 inch) required for the economical use of the recording medium would be very intractable. However, if the individual holograms were laid down in a series of strips across a one-inch (2·5 cm) wide tape, 40 holograms could be accommodated in each 0·6 mm-wide strip, giving a tape velocity of 15 cm/sec (6 in/sec). This would involve a method of scanning the recording or reading area transversely across the tape such that the full width of the tape was traversed in four milliseconds (or in other words, 250 traverses/sec occurred). This could be achieved (although with loss of overall optical efficiency) by arranging that during recording the region in which the holographic interference pattern was generated occupied the full width of the recording medium. The mask M (Figure 5) would consist of a disc with holes (0·6 mm diameter) spaced at one-inch (2·5 cm) intervals near its circumference, and rotated so that each hole in turn traversed the width of the tape. A rotating mask having 20 holes set in the circumference of a circle of radius 8 cm (3¼ in) and rotating at 750 r.p.m. would be suitable. The arrangement would be such that no exposure of the recording medium occurred except through the appropriate hole in the mask. The exposure time would be short enough to 'freeze' the tape motion* so that the recorded interference patterns were not blurred. On replay, the reconstruction beam would again be made wide enough to illuminate the complete tape width and a similar mask system (not shown in Figure 6) would select the hologram required for digit-beam reconstruction. The lens L_I would have an aperture which was larger than the tape width, so that all reconstructed digit-signal beams were collected. As the angle of emergence of a particular reconstructed digit beam is independent of the part of the hologram from which it is generated, light from each such beam will always fall onto the appropriate photo-diode irrespective of the position of the hole in the mask M across the tape.

If a packing density of 10^7 bits/cm^2 could be achieved (see Section 3.4) the tape velocity could be reduced by a factor of three relative to the value discussed above. A further reduction in tape velocity could also be made if the recording medium was capable of accepting volume holograms, and multiple exposure of the medium therefore became possible: the velocity reduction factor would be equal to the number of holograms that could be superimposed. Combining these two factors and assuming that ten holograms could be superimposed, the tape velocity required for the recording of a digital television signal onto one-inch (2·5 cm) wide tape would become 0·5 cm/sec (1/5 in/sec).

If the potentialities of the use of crystalline materials could be realised (see Section 3.4) an even more compact form of storage of digital signals would become available. The system[32] capable of storing 10^{12} bits/cm^3, for example, could store 10^4 seconds (about 2¾ hours) of digital television programme, or 10^6 seconds (about 11½ days) of stereo sound signal, per cubic centimetre of recording material.

3.5.3 The size and storage capacity of individual holograms

Apart from the high packing density that can be achieved in a holographic digital recording system, two other advantages of this system are important. In the first place, because the holographic pattern corresponding to each binary digit covers the entire surface area of an individual hologram, defects due to dust, blemishes etc. on the recorded hologram will not cause 'drop-outs' (i.e. the complete loss of one or more digit signals) to occur unless the defects are so large as to obscure a major part of the hologram. The effect of relatively small defects will instead show as a reduction in signal-to-noise ratio' (i.e. a reduction in the contrast between the digit beam and the background flare illumination) which will have no effect on the recovery of digital information until a certain threshold is reached. This advantage clearly becomes increasingly significant as the size of the individual holograms is increased. In the second place, a reduction in signal-to-noise ratio can also occur if the reconstruction beam falls onto a hologram adjacent to the one intended. Again this will have no effect on the reproduced digital signal until a definite tolerance limit is exceeded. The reduction in signal-to-noise ratio will in this case depend on the relative areas of the 'intended' and 'unintended' holograms illuminated by the reconstruction beam. As the size of the individaul holograms is increased, the absolute dimensional accuracy with which the reconstrcution beam must locate a hologram is therefore reduced, making for easier mechanical and optical design of the equipment. A further benefit of the use of large individual holograms is that the transverse velocity of the active area across the tape of recording medium (see Section 3.5.2) becomes less as the hologram size is increased, thus again making for a simpler mechanical arrangement.

The use of individual holograms of large area implies the use of a very large number of digit beams in order to preserve the intrinsic high packing density of the system (and therefore the low tape velocity). In fact, for constant packing density (or tape velocity) the required number of digit beams is proportional to the area of the individual hologram. As the number of digit beams is increased, the modulation depth of the holographic interference pattern corresponding to each beam decreases and the relative intensity of the reconstructed digit beams therefore also decreases. Signal-to-noise considerations therefore impose an upper limit on the number of digits that can be stored in one hologram: nevertheless it seems (see Section 3.5.2) that a sufficiently large number of digits can be so stored as to permit the development of a viable holographic digital recording system.

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*To restrict the movement of the tape to one-tenth of a wavelength of the light used during the exposure (say 60 nm) an exposure time of 400 nsec would be required if the tape velocity was 15 cm/sec.

3.5.4 Present-day feasibility of implementing a holographic digital recording system

It is unfortunately true that at present the use of a very large number of digit beams is not feasible. The principal limitation is the absence of a suitable method of digit-beam control. For the simultaneous control of a large number (up to 10^4) of digit beams some form of integrated array of light valves is required. Work on the development of such arrays using liquid crystal cells[36] or a moving membrane[37] has recently been reported, but no device is at present available having the required bandwidth. It is possible that 'magnetic bubble' domains[33] might prove useful as the basis of such an array,[38] since the domains may readily be created, annihilated and moved by currents in suitably-disposed conductors. They may be used for digit-beam control by virtue of the differential rotation of the polarisation of radiation passing through them relative to the radiation passing through the bulk of the magnetic material.

The use of a large number of digit beams also implies that the photo-electric cells used during replay should also be in the form of an integrated array, so that the image formed by the imaging lens (L_I in Figure 6) is of reasonable size. However, since such arrays find applications in 'solid state' television cameras, as well as in holographic 'read-only' computer memories[27], much effort has been directed to their development, and in fact arrays containing 2 x 10^5 phototransistors (400 rows and 500 columns) have been constructed.[34] It is not so certain, however, whether or not the addressing circuits associated with these arrays would at present be capable of handling the digital television data flow rate of 10^8 bits/second.

From the foregoing discussion it appears unlikely that a system exploiting in full the advantages of holographic digital storage can be developed in the immediate future. It would nevertheless be possible to consider a system (such as, for example, the one described by Hacking[16]) using a practiable number of digit beams and at the same time using an individual hologram size such as to give some degree of protection against dust particles and misdirection of the reconstructing beam. Although the packing density of such a system would be lower (probably by several orders of magnitude) than the greatest value offered by a holographic system, it might still possess advantages over other currently-available methods of digital recording (see Section 3.6), and in any case, its construction would provide valuable insight into the problems associated with holographic recording.

3.6 Comparison of holographic and other proposed digital recording systems

Digital recording systems are widely used for computer data storage, but no fully-developed system capable of handling the digital television information flow rate of 10^8 bits per second appears to exist at the present time. A number of systems do, however, exist which might be capable of development to the point at which this information flow rate could be handled. In the field of magnetic tape systems, for example, experimental equipment is being developed[35] based on longitudinal multi-track techniques. Indications are that this approach will yield a packing density of 1·3 x 10^5 bits/cm^2.

A number of systems which might, with development, be capable of handling real-time digital television signals have been discussed by Lunn and Moffatt,[14] and more recently by Jones.[35] One interesting system uses a focussed high-power laser beam to burn clear areas corresponding to individual binary digits in a specially developed opaque recording medium. The system as described uses holes of 1·5μm diameter separated by 3 μm and laid down in rows 4 μm apart (using a helical-scan system) and thus has a packing density of 8·3 x 10^6 bits/cm^2: the information flow rate is stated to be 2 x 10^7 bits per second*. It is claimed that the system has a potential packing density of 10^8 bits/cm^2 but that additional development work would be required for the recording of digital television signals. If this potential performance was achieved the packing density of the system would be about an order of magnitude higher than that estimated to be practicable (see Section 3.4) in a system using surface holograms: it would, however, have the disadvantage of requiring very accurate relocation of the individual binary digits on the recording medium during replay and would seemingly be very susceptible to 'drop-out' errors due to dust, etc. on the recording medium (although an error rate of 1 in 10^9 over the whole recording, storage and readout process is claimed).

Hacking's proposal[16] for a holographic recording system based on present-day technology uses small holograms recorded on conventional high resolution film, and achieves a packing density of 10^6 bits/cm^2 (about an order of magnitude greater than that of the magnetic tape system described above). A considerable degree of accuracy in relocating the individual holograms is still required by this system, although the use of the holographic technique permits about an order of magnitude less accuracy in both directions (i.e. between individual holograms and between rows of holograms) as compared with the 'individual binary digit' system.

4. Conclusions

An analogue television recording system could be developed using holographic techniques. Such a system would not, however, offer significant advantages over present-day analogue systems, except perhaps in the use of recording materials of greater durability.

Since the information flow rate in digital television signals is very high (10^8 bits per second), it is essential to achieve as high a packing density as possible of the information onto the recording medium, so as to keep the recording-medium transport velocity and the bulk of recording-medium used within practicable limits. Individual digits, if recorded in discrete form, will each occupy a very small area of the recording medium, and the reproduced signal will be very susceptible to errors arising from masking of these digits by dust particles and defects on the recording medium. A holographic system of recording would enable the digital information to be spread over an area of recording medium which is large compared with dust particles, etc., and thus would greatly reduce the errors in reproduction due to this cause. The use of a holographic technique also reduces the positioning accuracy required between the recorded information and the reproducing equipment: it can in addition lead to the use of relatively simple mechanical arrangements during the recording itself, but at the expense of increased optical and electronic complexity. A very high packing density can in principle be achieved using a holographic digital recording system, thus leading to very reasonable values of recording-medium velocity. Although an optimised holographic recording system cannot at present be implemented, because some optical components are not available in a suitable form, it would be practicalbe to develop a prototype system using existing components. Valuable experience would thus be gained in this field, and a system could emerge which, although not representing the best that could ultimately be achieved by the use of holographic techniques, might still be better than, say, magnetic-tape systems in terms of packing density and error rate in the reproduced signal. In the long term, it seems possible that a holographic digital recording system would enable extremely high packing-density values to be obtained.

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*This information flow rate is higher (by a factor of 20) than is required for a digital stereo sound signal.

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